Controlled rephasing of single collective spin excitations in a cold atomic quantum memory

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We demonstrate active control of inhomogeneous dephasing and rephasing for single collective atomic spin excitations (spin-waves) created by spontaneous Raman scattering in a quantum memory based on cold ^{87}Rb atoms. The control is provided by a reversible external magnetic field gradient inducing an inhomogeneous broadening of the atomic hyperfine levels. We demonstrate experimentally that active rephasing preserves the single photon nature of the retrieved photons. Finally, we show that the control of the inhomogeneous dephasing enables the creation of time-separated spin-waves in a single ensemble, followed by a selective readout in time. This is an important step towards the implementation of a functional temporally multiplexed quantum repeater node.

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Photonic quantum memories (QMs) [1–3] are devices which can faithfully store and retrieve quantum information encoded in photons. They are essential building blocks for scalable quantum technologies involving photons, such as linear optics quantum computing and long distance quantum communication using quantum repeaters [4–6]. QMs have been implemented with single atoms and ions [7–11], atomic vapors [12–21], and solid state systems [22–27].

Atomic ensembles provide an efficient way of reaching the strong interaction between matter and light required for the implementation of quantum memories, without the need for high finesse cavities. In addition, they give the possibility to multiplex quantum information, which is desirable in several applications. In particular, in quantum repeater architectures, this alleviates the limitation due to the communication time between the nodes [28]. In atomic ensembles, quantum information is stored as collective atomic spin excitations, called spin-waves. Single spin-waves offer the important advantage that they can be efficiently transferred to single photons in a well defined spatio-temporal mode thanks to constructive interference between the involved atoms. In 2001, Duan, Cirac, Lukin and Zoller (DLCZ) proposed a protocol to implement a quantum repeater using the heralded creation of spin-waves in an atomic ensemble [5]. Several demonstrations of the building block of the protocol have been reported [12, 16, 29] including functional elementary segments of a quantum repeater [30, 31]. Most of these demonstrations however, used only a single spin-wave per ensemble, although several ensembles have been already implemented in the same atom trap [32, 33].

A recent theoretical proposal has shown that the ability to precisely control the quantum state of single spin-waves would open new avenues for the realization of more efficient, temporally multiplexed quantum repeater architectures [34]. In particular, it has been proposed that the implementation of controlled dephasings and rephasings of single spin-waves would allow the creation of several time-separated single spin-waves in a single ensemble which could be selectively read out at different times. Rephasing protocols have also been proposed and implemented for optical collective atomic excitations, leading to the storage and retrieval of 64 weak optical modes in a rare-earth doped crystal [35], with pre-determined storage times. The capability to control the dephasing of spin-waves has also been used recently to implement a coherent optical pulse sequencer [36], efficient light storage for bright [37] and weak coherent pulses [17] using the gradient echo memory protocol [38], as well as storage of several temporal modes of bright pulses [37].

In this paper we demonstrate active control of the inhomogeneous dephasing and rephasing of single spin-waves stored in an atomic ensemble. A cold ^{87}Rb atomic ensemble QM is used to create heralded single spin excitations using the DLCZ scheme. We implement a controlled and reversible spin inhomogeneous broadening using a magnetic field gradient [38], leading to spin-wave dephasing and rephasing at a controlled time. We infer the dephasing and rephasing of the spin-waves by converting them into single photons. We show that with this ability, several temporally separated spin-waves can be stored and read out selectively. This is the first enabling step towards the implementation of a temporally multiplexed DLCZ quantum repeater, following the proposal of [34].

To implement a DLCZ QM, we start by an optically thick ensemble of N identical atoms exhibiting a Λ-type level scheme with two metastable ground states $|g\rangle$ and $|s\rangle$ and an excited state $|e\rangle$ (see Fig. 1(b)). All the atoms are initially prepared in $|g\rangle$. A weak, off-resonant write pulse on the $|g\rangle \rightarrow |e\rangle$ transition probabilistically creates a spin-wave heralded by a Raman scattered write photon. The write photons and the associated spin-waves

are described by a two-mode squeezed state as

$$|\phi\rangle = \sqrt{1-p}(|0_w\rangle\,|0_s\rangle + \sqrt{p}\,|1_w\rangle\,|1_s\rangle + p\,|2_w\rangle\,|2_s\rangle + o(p^{3/2})), \quad (1)$$

where p is the probability to create a spin-wave per trial in the detection mode, and w and s stand for write photon and spin-wave respectively. Upon detection of a write photon, the state of the associated spin-wave to first order is given by

$$|1_s\rangle = |\psi(0)\rangle = \frac{1}{\sqrt{N}}\sum_{j=1}^{N} e^{i\mathbf{x}_j\cdot(\mathbf{k}_W-\mathbf{k}_w)}\,|g_1\dots s_j\dots g_N\rangle\,, \quad (2)$$

where $\mathbf{x}_j$ is the position of atom j, and $\mathbf{k}_W$ and $\mathbf{k}_w$ are the wavevectors of the write pulse and write photonic mode respectively. The spin-wave can be read out at a later time with a counterpropagating read pulse resonant with the $|s\rangle \rightarrow |e\rangle$ transition. This converts the atomic excitation into a single read photon. Thanks to collective interference of all contributing atoms, the read photon is emitted in a well defined spatial mode given by the phase matching condition $\mathbf{k}_r = \mathbf{k}_R + \mathbf{k}_W - \mathbf{k}_w$, where $\mathbf{k}_R$ and $\mathbf{k}_r$ are the wavevectors of the read pulse and read photonic mode respectively. The retrieval efficiency is defined as $\eta_{ret} = p_{w,r}/p_w$, where $p_{w,r}$ is the probability per trial to detect a coincidence between write and read photons, and p_w is the probability to detect a write photon.

For the active rephasing experiment, we apply a magnetic field gradient to the ensemble during the storage of the spin-waves. This creates an inhomogeneous broadening of the hyperfine levels, due to the spatially dependent Zeeman shift and leads to a rapid dephasing of the spin-wave, with no further spontaneous rephasing. In this case, the state of the spin-wave evolves as

$$|\psi(t)\rangle = \frac{1}{\sqrt{N}}\sum_{j=1}^{N} e^{i\int_0^t \Delta\omega_j(t')dt' + i(\mathbf{x}_j+\mathbf{v}_j t)\cdot(\mathbf{k}_W-\mathbf{k}_w)}\,|g_1\dots s_j\dots g_N\rangle\,, \quad (3)$$

where $\Delta\omega_j(t)$ is the relative detuning of the state associated with atom j in $|s\rangle$, which is proportional to the magnetic gradient amplitude, and $\mathbf{v}_j$ is the velocity of atom j.

If we reverse the magnetic gradient at a time T_{rev}, a rephasing will be induced when $\int_0^{T_{rev}} \Delta\omega_j(t')dt' + \int_{T_{rev}}^{t} \Delta\omega_j(t')dt' = 0$, which happens at a time $2T_{rev}$ for a symmetric reversal, e.g. if $\Delta\omega_j(t \le T_{rev}) = -\Delta\omega_j(t \ge T_{rev})$. The retrieval efficiency at a time t is proportional to the overlap of the state at that time with the initial state: $\eta_{ret}(t) \propto |\langle\psi(0)|\psi(t)\rangle|^2$ [39]. Therefore, we use η_{ret} to monitor the spin-waves dephasing and rephasing in the following.

The experimental setup is shown in Fig. 1(a) [40]. We use an ensemble of laser cooled ^{87}Rb atoms loaded in a magneto optical trap (MOT), with a longitudinal magnetic gradient of 20G/cm along the probing axis. We address the D_2 line, which is resonant with light at 780 nm. The cooling laser, red detuned from the $|F=2\rangle \rightarrow |F'=3\rangle$ transition, and the repumper laser, resonant with the $|F=1\rangle \rightarrow |F'=2\rangle$ transition, will be referred to as the trapping beams. All the atoms are initially optically pumped in the $|g, m_F=2\rangle$ Zeeman sublevel, permitting us to create a magnetically sensitive spin-wave, which is necessary for this experiment. The write pulse is red detuned by 40 MHz from the $|g\rangle \rightarrow |e\rangle$ transition and has a duration of 16 ns. With these parameters, a peak power of 590 μW leads to a write photon detection probability p_w of 1%. The read pulse, counterpropagating with the write pulse, is resonant with the $|s\rangle \rightarrow |e\rangle$ transition and has a duration of 20 ns. A peak power of 570 μW maximizes the retrieval efficiency. The polarization of the write and read pulses in the frame of the atoms is σ^- and σ^+ respectively, while the detected write and read photons are σ^+ and σ^- polarized. We set an angle of 0.95° between the write/read pulses axis and the photons detection axis, to spatially separate the classical pulses from the write and read photons. The write and read photons are spectrally filtered by identical monolithic Fabry-Perot cavities with 20 % total transmission (including cavity transmission, subsequent fiber coupling and spectrum mismatch between the single photons and the cavity mode), before detection by single photon detectors (SPDs) with 43 % efficiency.

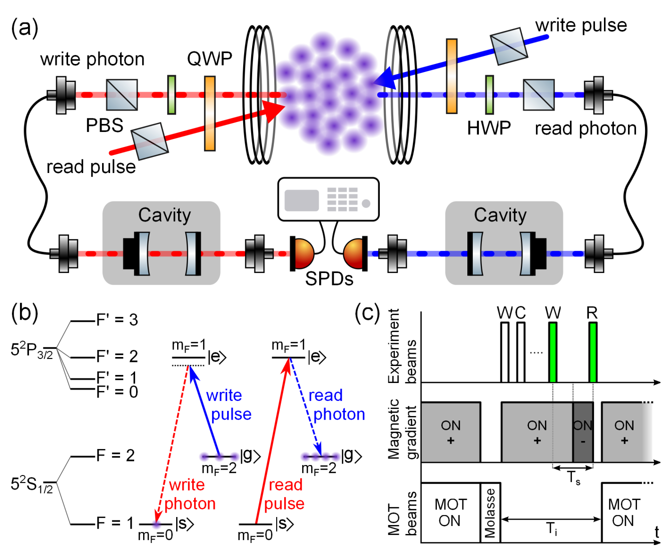

FIG. 1: (color online) (**a**) Schematic of the experimental setup. HWP: half-wave plate, QWP: quarter-wave plate, PBS: polarizing beam splitter, SPD: single photon detector. (**b**) Energy levels structure. (**c**) Experimental sequence timeline for the active rephasing experiment. W: write pulse, C: cleaning stage, R: read pulse, T_s: storage time, T_i: interrogation time

The experimental sequence for the active rephasing experiment is shown in Fig. 1(c). After a MOT loading

phase of 15 ms, we switch off the MOT gradient while the trapping beams are kept on during a molasses (1.6 ms) phase. Afterwards, we perform optical pumping for 10 μs. The measured optical depth at this stage is 6 ± 1. The magnetic gradient is then switched on again before the beginning of an interrogation period of up to 660 μs during which a train of up to 200 write pulses is sent. For each trial, if no write photon is detected, a cleaning stage sets the memory back into its initial state. It consists of an optical pumping pulse, which is σ^+ polarized and resonant with the $|F=2\rangle \rightarrow |F'=3\rangle$ transition, and read light. If instead a write photon is detected, we reverse the magnetic gradient and send a read pulse after a programmable delay. This leads to the end of the interrogation of the current ensemble and to the loading of a new one with a repetition rate of 59 Hz.

We now present the experimental results. We start by measuring the retrieval efficiency η_{ret} as a function of storage time, for a standard DLCZ experiment, i.e. when no magnetic gradient is applied during the interrogation period. The results are shown in Fig. 2 (open circles). We observe an oscillation which can be attributed to a beating between two different classes of spin-waves due to imperfect optical pumping into the $|g, m_F = 2\rangle$ state [41, 42]. The overall decay in retrieval efficiency has a time constant of $57 \pm 1\,\mu$s, limited by atomic motion [21, 39] and spurious magnetic field gradients [43]. We then switch on the gradient during the interrogation period. In that case, we observe a rapid dephasing of the spin-wave at short storage times (see left inset), followed by background noise for a period of about 20 μs. If the gradient is reversed after the detection of a write photon, we observe a rephasing, witnessed by a pronounced increase in retrieval efficiency. The measured efficiencies after the rephasing are again at the noise level. The reversal instruction is sent 3 μs after the write pulse, but due to the temporal response of the coils driving circuit, the rephasing occurs at 20.84 μs (see right inset). The full width at half maximum of the rephasing peak is 150 ± 3 ns, and its position can be precisely modified by changing the magnetic gradient reversal time [42].

The retrieval efficiency at the rephasing peak is about 60% of the retrieval efficiency in the standard DLCZ experiment for the same storage time [42]. Several effects may explain this reduction. First, slow fluctuations of the current in the coils generating the magnetic field gradient can change the position of the rephasing peak during the measurement time, which will decrease the efficiency for a given read-out time. Moreover, time varying magnetic field gradients over the interrogation time lead to fluctuations of the rephasing time depending on the write photons detection time. Finally, the quality of the optical pumping may be degraded during the interrogation period because of the presence of the magnetic field gradient. This decreases the optical depth and therefore the efficiency. The experimental data are fitted based on equation (3), corrected for the memory lifetime and the temperature drift of the read photons filtering cavity during the measurement time (see [42]). The signal to noise ratio (SNR), calculated as the maximum value of the fit at the rephasing time divided by the mean of the background, is 13.3 ± 0.9.

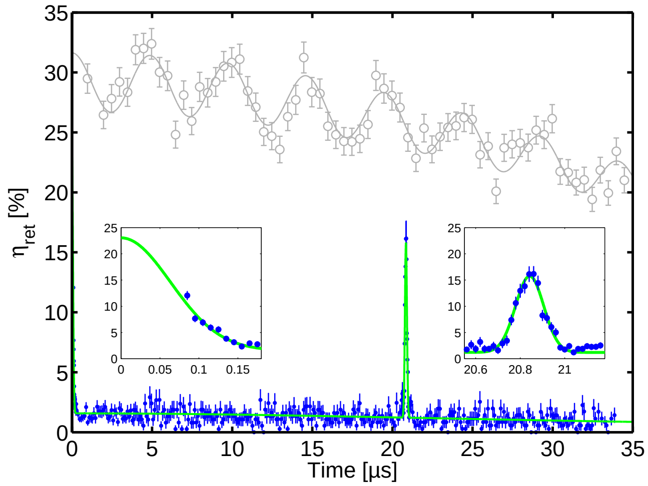

FIG. 2: (color online) Retrieval efficiency vs. readout time for $p_w = 1\%$. (grey open circles) Standard DLCZ experiment. The oscillations are due to imperfect optical pumping. (grey line) Fit of the experimental data. (blue dots) Active rephasing experiment. (green line) Fit of the experimental data.

Next, we investigate the single photon nature of the rephased read photons. For this measurement, we modified the setup by sending the read photons through a balanced fiber beamsplitter connected to two SPDs. We measured the antibunching parameter α of the read photons [44] defined as

$$\alpha = \frac{p_{w,r_1,r_2} \cdot p_w}{p_{w,r_1} \cdot p_{w,r_2}}, \tag{4}$$

where p_{w,r_1,r_2} is the probability to measure a triple coincidence between a write photon and both read photons detections, and p_{w,r_1}, p_{w,r_2} are the probabilities to measure a coincidence between a write photon and either one of the read photon detections. The measured values of α as a function of p_w in the case of the active rephasing experiment are shown in Fig. 3. An antibunching parameter lower than 1 is a proof of non-classicality, 1 corresponding to coherent states and 0 to perfect single photons. We expect to be in the single photon regime for low excitation probabilities. We observe values below 1 within the error for p_w up to 0.5 %, with values as low as 0.20 ± 0.14 for $p_w = 0.17\%$. The data are fitted using the formula $\alpha = 2p(2c(1+p) - p)/(c(1+p))^2$, where c is the proportionality factor between the real and ideal $g^{(2)}_{w,r}$, the cross-correlation function between write and read photons (see [42]).

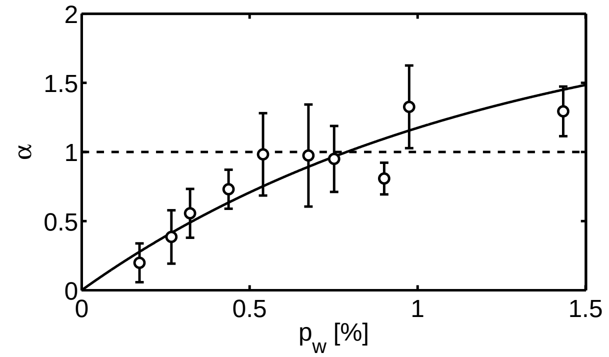

FIG. 3: Antibunching parameter as a function of write photon detection probability. Open circles: experimental data. The dashed line represents the limit for classical states ($\alpha \geq 1$).

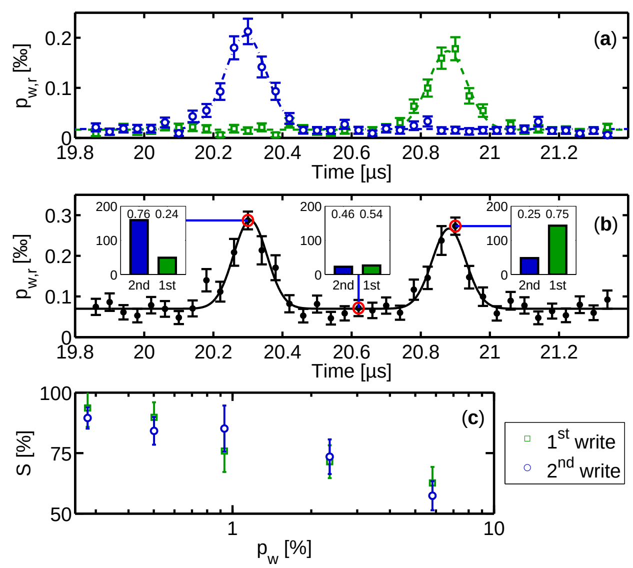

FIG. 4: (Color online) Temporally separated spin-waves. (**a**) Single rephasing case for $p_w = 1\%$: first write pulse in green, second write pulse in blue. (**b**) Both pulses sent in black. The histograms display the relative weight of each peak, at the circled points. (**c**) Selectivity as a function of p_w for each rephasing.

It has been predicted that the controlled dephasing and rephasing of single collective excitations as demonstrated in this paper should enable the creation of multiple time-separated spin-waves that can be selectively read-out in time [34]. To confirm this prediction, we send two write pulses separated by 600 ns, first independently and then conjointly before performing the readout around the rephasing time. Fig. 4 (a) shows the coincidence probabilities per trial $p_{w,r}$ when each write pulse is send independently. The readout time is defined as the time between the first write pulse and the read pulse. As expected, the spin-wave created by the first write pulse rephases later and vice versa. Fig. 4 (b) shows the coincidence probability when both write pulses are sent conjointly. The values at the maximum of the rephasing peaks are similar, when background-subtracted. However, the background probability outside the rephasing peaks is higher in this case. This can be explained by expressing the coincidence probability in the background outside the rephasings as $p_B = p_w \cdot p_r$. Noting that $p_r \propto p_w$ [45], one gets $p_B \propto p_w^2$. In the case where we send two write pulses, the write detection probability p_{2w} is twice the one of the single write pulse case p_w. Therefore, the background probability for two write pulses becomes $p_B^{(2)} \propto p_{2w}^2 = 4 * p_w^2$. This is compatible with the measured value of 4.1 ± 0.3.

To investigate the cross-talk between the two spin-waves, we construct the histograms shown in the insets by performing start-stop measurements. The starts are write photon detections, and the stops are read photon detections. The two contributions are equally weighted in the noise region, but on each rephasing peak, we detect a significant imbalance. This shows that mostly only one spin-wave rephases at a time. To quantify the process, we calculate the relative weight of each peak, which we call selectivity: $S(i) = p_{C,i} / \sum_k p_{C,k}$, with $p_{C,i}$ the probability to detect a coincidence in the binning corresponding to the peak number i. Its value depends on the rephasing SNR which varies with p_w (see Fig. 4 (c) and [42]). For the results shown in Fig. 4 (b) we find $S = (S(1) + S(2))/2 = 76 \pm 6\%$. For lower $p_w = 0.28\%$, we obtain a selectivity of $92 \pm 4\%$.

The results of Fig. 4 show that when several spin-waves are created, the rephasing efficiency of each one remains the same, but the background noise increases. With the current status of the experiment, this limits the benefit of multiple temporal mode storage, since the excitation probability needs to be reduced for each pulse in order to keep the same SNR. However, this issue is addressed in the scheme proposed in [34]. A possible solution would be to build a low finesse cavity resonant with the write photons but invisible to the read photons around the QM. This would decrease the proportion of unwanted spin-waves created per write pulse by increasing the proportion of write photons emitted in the cavity mode. Therefore, the noise would decrease by a factor corresponding to the cavity finesse.

In conclusion, we demonstrated active rephasing of a single spin-wave at a controllable time by inverting the polarity of an external inhomogeneous broadening created by a magnetic gradient. We showed that in this case, the retrieved photons still exhibit antibunching, which proves that active rephasing preserves single photons statistics. Finally, we demonstrated experimentally that this technique enables the creation of multiple time-separated spin-waves that can be read-out with high selectivity in time. These results pave the way towards the realization of a temporally multiplexed DLCZ-type

quantum repeater node.

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Note added.– Related works demonstrating spin echoes at the single excitation level in rare-earth doped crystals [46] and cold atomic ensembles [47] have recently been reported.

[1] A. I. Lvovsky, B. C. Sanders, and W. Tittel, Nat Photon **3**, 706 (2009).
[2] K. Hammerer, A. S. Sørensen, and E. S. Polzik, Rev. Mod. Phys. **82**, 1041 (2010).
[3] F. Bussières *et al.*, Journal of Modern Optics **60**, 1519 (2013).
[4] H.-J. Briegel, W. Dür, J. I. Cirac, and P. Zoller, Phys. Rev. Lett. **81**, 5932 (1998).
[5] L.-M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, Nature **414**, 413 (2001).
[6] N. Sangouard, C. Simon, H. de Riedmatten, and N. Gisin, Rev. Mod. Phys. **83**, 33 (2011).
[7] S. Ritter *et al.*, Nature **484**, 195 (2012).
[8] D. L. Moehring *et al.*, Nature **449**, 68 (2007).
[9] J. Hofmann *et al.*, Science **337**, 72 (2012).
[10] A. Stute *et al.*, Nature **485**, 482 (2012).
[11] M. Schug *et al.*, Phys. Rev. Lett. **110**, 213603 (2013).
[12] C. W. Chou *et al.*, Nature **438**, 828 (2005).
[13] T. Chanelière *et al.*, Nature **438**, 833 (2005).
[14] M. D. Eisaman *et al.*, Nature **438**, 837 (2005).
[15] K. S. Choi, H. Deng, J. Laurat, and H. J. Kimble, Nature **452**, 67 (2008).
[16] A. G. Radnaev *et al.*, Nat Phys **6**, 894 (2010).
[17] M. Hosseini *et al.*, Nat Phys **7**, 794 (2011).
[18] M. Sprague *et al.*, Nat Photon **8**, 287 (2014).
[19] X.-H. Bao *et al.*, Nat Phys **8**, 517 (2012).
[20] E. Bimbard *et al.*, Phys. Rev. Lett. **112**, 033601 (2014).
[21] A. Nicolas *et al.*, Nat Photon **8**, 234 (2014).
[22] H. de Riedmatten *et al.*, Nature **456**, 773 (2008).
[23] M. P. Hedges, J. J. Longdell, Y. Li, and M. J. Sellars, Nature **465**, 1052 (2010).
[24] C. Clausen *et al.*, Nature **469**, 508 (2011).
[25] E. Saglamyurek *et al.*, Nature **469**, 512 (2011).
[26] D. Rieländer *et al.*, Phys. Rev. Lett. **112**, 040504 (2014).
[27] H. Bernien *et al.*, Nature **497**, 86 (2013).
[28] C. Simon *et al.*, Phys. Rev. Lett. **98**, 190503 (2007).
[29] A. Kuzmich *et al.*, Nature **423**, 731 (2003).
[30] C. W. Chou *et al.*, Science **316**, 1316 (2007).
[31] Z.-S. Yuan *et al.*, Nature **454**, 1098 (2008).
[32] S.-Y. Lan *et al.*, Opt. Express **17**, 13639 (2009).
[33] K. S. Choi *et al.*, Nature **468**, 412 (2010).
[34] C. Simon, H. de Riedmatten, and M. Afzelius, Phys. Rev. A **82**, 010304 (2010).
[35] I. Usmani, M. Afzelius, H. de Riedmatten, and N. Gisin, Nat Commun **1**, 12 (2010).
[36] M. Hosseini *et al.*, Nature **461**, 241 (2009).
[37] M. Hosseini *et al.*, Nat Commun **2**, 174 (2011).
[38] G. Hétet *et al.*, Opt. Lett. **33**, 2323 (2008).
[39] B. Zhao *et al.*, Nat Phys **5**, 95 (2009).
[40] B. Albrecht *et al.*, Nat Commun **5**, (2014).
[41] R. Zhao *et al.*, Nat Phys **5**, 100 (2009).
[42] See Supplemental Material.
[43] D. Felinto *et al.*, Phys. Rev. A **72**, 053809 (2005).
[44] P. Grangier, G. Roger, and A. Aspect, EPL (Europhysics Letters) **1**, 173 (1986).
[45] S. Chen *et al.*, Phys. Rev. Lett. **97**, 173004 (2006).
[46] P. Jobez *et al.*, arXiv:1501.03981 (2015).
[47] J. Rui *et al.*, arXiv:1501.06278 (2015).